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Our research under the RASSP program focussed on the development of new signal processing algorithms to exploit the advantages and opportunities of rapid prototyping for signal processing systems. Our work was carried out in the Research Laboratory of Electronics at MIT with close collaboration and interaction with industrial partners including Lockheed Sanders.

Our primary accomplishments were in several categories. We developed and explored new classes of signals and algorithms related to chaotic behavior in nonlinear systems. We also developed and explored the use of fractal signals for communications. A third new nonlinear signal class that we explored exploits the soliton behavior of certain nonlinear wave equations.

A significant part of our effort was directed at the exploration of algorithm-based fault tolerant architectures for signal processing and for the use of approximate processing techniques which can be exploited in the contexts of low-power signal processing architectures and in other aspects of processor resource management. We also explored opportunities to exploit multirate signal processing.

In the following section we briefly summarize our results in each of these areas. Section 3 contains a bibliography of the journal articles, book chapters, and conference papers in which the details of our work is presented.

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Numerical and Symbolic Algorithms for Application Specific Signal Processing

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1 Introduction

Our research under the RASSP program focussed on the development of new signal processing algorithms to exploit the advantages and opportunities of rapid prototyping for signal processing systems. Our work was carried out in the Research Laboratory of Electronics at MIT with close collaboration and interaction with industrial partners including Lockheed Sanders.

Our primary accomplishments were in several categories. We developed and explored new classes of signals and algorithms related to chaotic behavior in nonlinear systems. We also developed and explored the use of fractal signals for communications. A third new nonlinear signal class that we explored exploits the soliton behavior of certain nonlinear wave equations.

A significant part of our effort was directed at the exploration of algorithm-based fault tolerant architectures for signal processing and for the use of approximate processing techniques which can be exploited in the contexts of low-power signal processing architectures and in other aspects of processor resource management. We also explored opportunities to exploit multirate signal processing.

In the following section we briefly summarize our results in each of these areas. Section 3 contains a bibliography of the journal articles, book chapters, and conference papers in which the details of our work is presented.

2 Research Summaries

2.1 Signal Processing Based on Chaotic Systems

A considerable part of our research was directed at developing new classes of signals and algorithms related to chaotic behavior in nonlinear systems.

One area explored was robustness and signal recovery in synchronized chaotic systems. This work led to an approximate analytical model that quantified and explained the observed robustness and synchronization in the Lorenz system, in particular it explained why speech and other narrowband perturbations can be recovered faithfully, even though the synchronization error is comparable in power to the message itself.

Other work developed a systematic approach for synthesizing dissipative chaotic arrays that possess the self-synchronization property. We found that the ability to synthesize high-dimensional chaotic arrays further enhances

the usefulness of synchronized chaotic systems for communications, signal processing, and modeling of physical processes.

We also developed a method to analyze a DC-DC converter operating in its chaotic regime, by using a nonlinear, first-order state-variable, sampled-data circuit model. In contrast to traditional time-averaging techniques, which rely on the periodicity of the relevant waveforms, our averaging techniques rely on a property analogous to *ergodicity* in the theory of stochastic processes which allows time averages to be expressed in terms of an integral with respect to a certain "probability density." This approach can be used to determine a relation between the circuit parameters and the input-output voltage gain of the converter, and to illustrate some of the bifurcation behavior of the circuit.

More recent work under the RASSP program explored signal estimation from an encoding in the form of quantized noisy measurements. We've demonstrated that the use of an appropriately designed and often easily implemented additive control input before signal quantization at the sensor can significantly enhance overall system performance. In particular we've developed efficient estimators in conjunction with optimized pseudonoise, deterministic, and feedback-based control inputs, and have showed that these lead to a hierarchy of practical systems with very performance-complexity characteristics.

2.2 Wavelet-based Analysis and Synthesis for Communication Systems

Another important part of this program involved developing and exploring the use of fractal signals for communications.

Fractal point processes are increasingly being viewed as important models for a host of natural and man-made phenomena. To adequately exploit such models, efficient techniques for processing, analyzing, and synthesizing fractal point processes in the context of such applications are required. Our work has developed a broad set of practical results for an important class of quasi-stationary fractal point processes we refer to as fractal renewal processes. Starting from an engineering-oriented mathematical characterization of such processes, we've formulated a novel multiscale framework, based on random mixture of Poisson constituents, for these processes, which serves as the foundation for analysis and algorithm development.

Using this framework, efficient signal processing algorithms have been developed for fractal renewal processes, including a synthesis which requires a single Poisson process generator for its implementation. Included are a continuous-scale version for exact synthesis, and a discrete-scale version for arbitrarily accurate synthesis using a countable collection of constituents. Complementary multiscale analysis algorithms have also been developed, aimed primarily at robust parameter and signal recovery in a noise-corrupted scenario. More specifically, we've derived a maximum-likelihood fractal dimension estimator and a Bayes' least-squares interarrival estimator. Performance has been evaluated using simulations and theoretical bounds.

We have obtained characterizations of fractal renewal processes in familiar discrete-event systems, particularly networks and queues, by using multiscale methods. Our results have suggested invariance of key fractal properties under traffic branching and merging.

We have also explored a number of problems of network design and management. Optimal multiscale server control policies have been developed for queuing systems with fractal traffic input, which exploit past history of traffic to enhance performance. In comparison with policies which ignore past history, our multiscale controller is superior in terms of average individual waiting time and service costs.

Also during the period of our grant, we have developed a class of practical, low-complexity, variable-rate coding schemes for communication over channels with feedback. We've shown that for arbitrary discrete memoryless channels with noise-free feedback, these schemes achieve error probabilities that decay exponentially with blocklength at any rate below the channel capacity. Moreover, we've found that the error exponent associated with these schemes is shown to be higher than the random-coding exponent. We've developed extensions of the strategy for use on channels with memory, unknown channels (universal decoding), and channels with noisy and delayed feedback.

2.3 Communications Based on Soliton Systems

Another area explored under the RASSP program was the soliton behavior of certain nonlinear wave equations. Solitons are eigenfunction solutions to certain nonlinear wave equations that arise in a variety of natural and man-made systems. Their dynamics and tractable mathematical structure make them an intriguing component of such systems, often describing large

scale or long term behavior of natural systems, or the information content in certain communication or signal processing systems. It is often difficult to detect or estimate the parameters of solitons in such systems due to the presence of strong non-soliton components, or due to the nonlinear interaction of multiple solitons. In order to investigate the detection and estimation of these soliton signals, we have considered using these nonlinear systems as both signal generators and signal processors in a form of multiplexed soliton communication. Our communication system uses soliton systems for signal generation and multiplexing for transmission over traditional linear channels. We have found that soliton signal dynamics may also provide a mechanism for decreasing transmitted signal energy while enhancing signal detection and parameter estimation performance.

We have also exploited soliton systems as specialized signal processors which are naturally suited to a number of complex signal processing tasks. We have explored new circuit models for two soliton systems, the Toda lattice and the discrete-KdV equations. These analog circuits can generate and process soliton signals and can be used as multiplexers and demultiplexers in a number of potential soliton-based wireless communication applications. The Toda lattice model appears to be the first such circuit sufficiently accurate to demonstrate true soliton collisions and the discrete-KdV equation has provided a convenient means for processing discrete-time soliton signals.

2.4 Fault-Tolerant Signal Processing

An important part of our effort was also directed at the exploration of algorithm-based fault tolerant architectures. The traditional approach to fault-tolerant computation has been via modular hardware redundancy. Although universal and simple, modular redundancy is inherently expensive and inefficient. We've found by exploiting particular structural features of a computation or an algorithm to introduce "analytical redundancy," arithmetic codes and recently developed Algorithm-Based Fault Tolerance (ABFT) techniques manage to offer more efficient fault coverage at the cost of narrower applicability and harder design. Earlier work we've done has shown that a variety of useful results and constructive procedures can be obtained when the computation takes place in an *abelian group*. In our more recent work we've developed a systematic algebraic approach for computations that occur in *semigroups*. We've extended the framework to a more general setting with wider potential applicability, for example to finite state

machines and nonlinear signal processing. In particular, we've illustrated the use of our algebraic results by designing ABFT for *group/semigroup* state machines and *finite automata.*

2.5 Approximate Signal Processing

Another significant part of our research during the grant period was investigating approximate processing techniques which can be exploited in the contexts of low-power signal processing architectures and in other aspects of processor resource management. It is increasingly important to structure signal processing algorithms and systems to allow for trading off between the accuracy of results and the utilization of resources in their implementation.

We have found a probabilistic complexity analysis of a class of multi-stage algorithms which incrementally refine DFT approximations. Each stage of any algorithm in this class refines the results of the previous stage by a fixed increment in one of three dimensions: SNR, frequency resolution, or frequency coverage. However, the complexity of each stage is probabilistically dependent upon certain characteristics of the input signal. Assuming that an algorithm has to be terminated before its arithmetic cost exceeds a given limit, we have formulated a method for predicting the probability of completion of each of the algorithm's stages. Our analysis is useful for low-power and real-time applications where FFT algorithms cannot meet the specified limits on arithmetic cost.

Work has also been done based on the concepts of adaptive filtering and approximate processing when approaching design of low-power frequency selective digital filters. This approach uses a feedback mechanism in conjunction with well-known implementation structures for FIR and IIR digital filters. The algorithm designed reduces the total switched capacitance by dynamically varying the filter order based on signal statistics.

2.6 Multirate Signal Processing

Multirate systems and filterbanks have traditionally played an important role in source coding and compression for contemporary communication applications, and many of the key design issues in such applications have been extensively explored. In our research under the RASSP program, we have reviewed recent developments on the comparatively less explored role of multirate filterbanks and wavelets in channel coding and modulation for some

important classes of channels. We have found several emerging potential applications. One involves the use of highly dispersive, broadband multirate systems for wireless multiuser communication in the presence of fading due to time-varying multipath. Another is the wavelet-based diversity strategy referred to as "fractal modulation" for use with unpredictable communication links and in broadcast applications with user-selectable quality of service. Another involves multitone (multicarrier) modulation systems based on multirate filterbanks and fast lapped transforms for use on channels subject to severe intersymbol and narrowband interference.

We have also developed and explored a class of powerful and computationally efficient strategies for exploiting transmit antenna diversity on fading channels. We have found that these strategies, which require simple linear processing at the transmitter and receiver, have attractive asymptotic characteristics. Specifically, given a sufficient number of transmit antennas, these techniques effectively transform a nonselective Rayleigh fading channel into a nonfading, simple white marginally Gaussian noise channel with no intersymbol interference. These strategies, which we refer to as linear antenna precoding, can be efficiently combined with trellis coding and other popular error-correcting codes for bandwidth-constrained Gaussian channels. Linear antenna precoding requires no additional power or bandwidth and is attractive in terms of robustness and delay considerations.

Another area of multirate signal processing we've explored during the period of the grant is spread-response precoding for communication over fading channels. We've developed this as an alternative to interleaving, which is the usual technique for improving the effectiveness of traditional error-correcting codes in data transmission systems that exhibit multipath fading. From the perspective of the coded symbol stream, spread-response precoding effectively transforms an arbitrary Rayleigh fading channel into a nonfading, simple white marginally Gaussian noise channel. We've found that spread-response precoding requires no additional power or bandwidth, and is attractive in terms of computational complexity, robustness and delay considerations.

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